

文章编号:1000-8055(2013)09-2100-12

Influence of fuel injection position and equivalent mixture ratio on chemical non-equilibrium effects of single expansion ramp nozzle

CHENG Cheng, WANG Yi-bai, LIU Yu, QIN Li-zi

(School of Astronautics,
Beijing University of Aeronautics and Astronautics, Beijing 100191, China)

Abstract: Chemical non-equilibrium flow was investigated for the scramjet single expansion ramp nozzle (SERN) with a strut-based liquid-kerosene-fueled combustor. Two-dimensional Reynolds-averaged Navier-Stokes(RANS) equations were solved with the species conservation equation for continuous phase and the renormalization group(RNG) $k-\epsilon$ turbulence model. Lagrangian discrete-phase model was analyzed for liquid-kerosene droplets behavior in the supersonic stream. Combustion was simulated by kerosene surrogate fuel's 10-species and 13-step reduced reaction kinetics mechanism with use of Arrhenius's laminar finite rate model. Parametric studies were carried out to estimate the influence of different fuel injection positions and equivalent mixture ratios on the SERN chemical non-equilibrium effects. Numerical calculation results show that the strut-based combustor enables convenient modeling of various SERN entry conditions, which is similar with many preceding investigations, by changing the injector strut position and controlling the mass flow rate of each injector. Chemical non-equilibrium effects function in the whole SERN, especially in the initial flow expansion region, leads to obviously higher SERN performance of the non-equilibrium flow than that of the frozen flow. Furthermore, the distributed fuel injection pattern plays a significant role in enhancing the combustion efficiency in combustor, but weakening the chemical non-equilibrium effects function in SERN. Additionally, while the equivalent mixture ratio increases, the SERN thrust coefficient and lift coefficient rise gradually, and the increment of non-equilibrium flow in relation to frozen flow becomes higher as well. To be specific, the equivalent mixture ratio is 0.6, the maximum increment of thrust coefficient and lift coefficient are 11.6% and 25% respectively.

Key words: scramjet engine; single expansion ramp nozzle; chemical non-equilibrium;
fuel injection position; equivalent mixture ratio

CLC number: V231.2

Document code: A

Liquid hydrocarbon fuel, such as aviation kerosene, is desirable and most promising in lower hypersonic regions ($Ma < 8$) that are current interest, in view of its higher volumetric energy content, lower cost, and relative ease of handling, etc. However, atomization, vaporization, and mixing are some of the major barriers in the liquid-kerosene-based scramjet combustor. Furthermore, the kerosene fuel is composed of a variety of hydrocarbons (from C_9 to C_{16}),

leading to multi-level physical-chemical combustion reactions, which increases the delay time of heat release, whereas the flow residence time in scramjet combustor is very short (several milliseconds)^[1]. All these issues contribute to the generally low combustion efficiency of liquid-kerosene-based scramjet. As a result, the influence of residual fuel combustion in scramjet tail nozzle on engine performance can not be ignored and, in addition, a considerable fraction of dis-

Received: 2012-09-20

URL: http://www.cnki.net/kcms/detail/11.2297.V.20130926.1103.201309.2100_015.html

E-mail: ccheng.buaa@gmail.com

sociated combustion products due to the high temperature in combustor carries recombination reaction and releases heat during flow expansion in the scramjet nozzle. Hence, the chemical non-equilibrium effects should be taken into account for kerosene-based scramjet nozzle performance. Recently, research on supersonic combustion of kerosene has made a great progress at home and abroad^[2-3], but few scholars conduct an investigation on chemical non-equilibrium flow of residual kerosene and combustion products reaction in scramjet nozzle. WANG et al. and Thomas et al.^[4-5] numerically simulated the non-equilibrium expansion flow of hydrogen-fueled scramjet nozzle respectively, and indicated that the chemical non-equilibrium has a noteworthy impact on performance of scramjet nozzle. Besides, chemical non-equilibrium effects have attracted serious attention on the high-enthalpy shock tunnel study^[6].

The entry conditions of scramjet nozzle are serious non-uniform because of the particular combustor structure, and have tremendous influences on the reaction processes and thrust characteristics. To predict the nozzle flow-field accurately, it is necessary to use a simplified combustor to simulate the scramjet nozzle entry conditions. Several fuel-injection strategies, such as strut^[7], wall^[8], ramp^[9], and cavity configurations^[10], have been investigated in full-scale combustors in the recent past. The strut-based combustor could simulate different scramjet nozzle inlet conditions more conveniently by controlling the mass flow of each strut injector. A large number of experimental and numerical studies were reported in the literatures to focus on various aspects of flow phenomena in strut-based scramjet combustors^[7,11-13]. The optimum kerosene flow rate distribution through different strut injectors that gives the maximum combustor efficiency along with the minimum pressure loss and the maximum uniformity in the exit static temperature has been discussed by Ramya and Marathe^[14]. In addition, in the preceding numerical simulations^[7,13,15], the Lagrangian tracking method was used for discrete-phase

model (DPM) to characterize the flow behavior of the liquid kerosene, and the fuel injector was modeled as surface injector, wherein droplets were injected with constant diameter.

In this work, numerical simulations have been carried out to investigate the chemical non-equilibrium flow and thrust characteristics of scramjet nozzle with kerosene-fueled strut-based combustor and Lagrangian discrete-phase model. The chemical non-equilibrium effects of scramjet nozzle are estimated with different kerosene injection positions and equivalent mixture ratios.

1 Computational configuration

As a typical scramjet nozzle structure, the SERN has the advantage of minimizing friction drag and nozzle weight while extracting thrust from the high-pressure flow on the scramjet aft-body. In the present work, an approximate Rao's nozzle approach^[16] has been proposed to establish the computational SERN model shown in Fig. 1. The ramp consists of a short entrance with radius $R_d = 0.225$ and the Rao's spline curve BE with initial expansion angle $\beta_B = 32.7^\circ$ and exit angle $\beta_E = 5.7^\circ$. With divergence angle $\theta = 3^\circ$, the cowl's length L_s is 4, and the SERN total length L and exit height H_2 are 18.08 and 5.52, respectively. Here all of the lengths are non-dimensionalized with the nozzle inlet height H_1 .

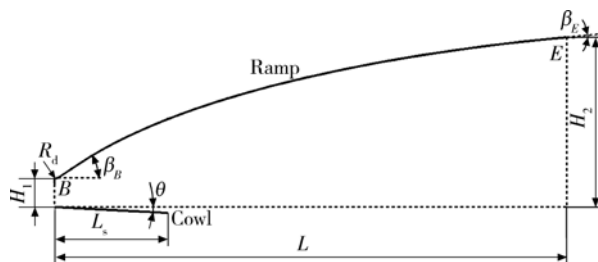


Fig. 1 Schematic of single expansion ramp nozzle

To predict the chemical non-equilibrium flow in scramjet SERN accurately, a strut-based combustor is used to simulate the nozzle entry conditions in this work. The geometry and mesh of the combustor with strut arrangement is given in Fig. 2, and a close-up view of the strut is shown in Fig. 3. The combustor has a total of

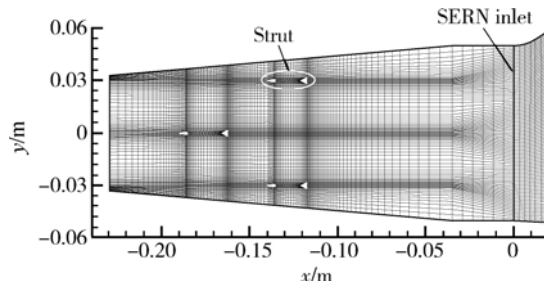


Fig. 2 Geometry and mesh of strut-based combustor

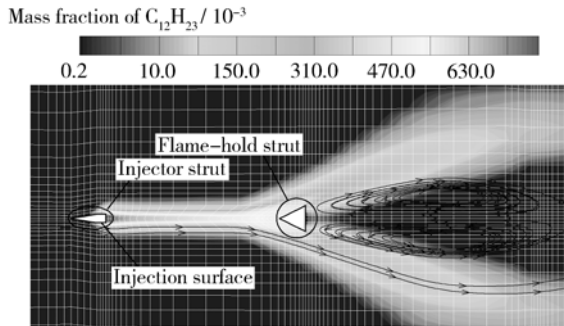


Fig. 3 Close-up view of strut

three groups of struts distributed in two stages. Each strut group consists of an injector strut located upstream and a followed flame-hold strut. The sharp leading edges of injector strut are designed to keep the shock attaching, and the trailing edges are parallel with mainstream for fuel injection. The flame-hold strut with a 55° leading-edge angle is provided for flame stabilization and to enhance mixing. The spanwise staggered arrangement of the struts could conveniently simulate different scramjet SERN entry conditions by controlling the mass flow rate of each strut injector, and together with the divergence provided on the combustor walls intend to avoid thermal choking for operating conditions studied in this paper. Kerosene is injected from the injection surfaces (each of 1 mm in length) in the transverse direction (i. e., in the positive and negative y direction). Since the injector dimension is exceedingly small compared with the dimensions of the strut-based combustor and SERN, very fine meshing is necessary to have at least a few facets on the injection surface. The whole computational domain is discretized by 22 818 quadrilateral grids, and 12 698 cells

therein belong to the strut-based combustor.

2 Methodology

2.1 Governing equations

In the simulations, two-dimensional compressible and turbulent Reynolds-averaged Navier-Stokes equations are solved along with the species conservation equation for the continuous phase. In a Cartesian coordinate system, the aforesaid RANS can be written in vector notation as

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{E}}{\partial x} + \frac{\partial \mathbf{F}}{\partial y} = \frac{\partial \mathbf{E}_v}{\partial x} + \frac{\partial \mathbf{F}_v}{\partial y} + \mathbf{H} \quad (1)$$

where, $\mathbf{U}$ is the conservative variable; $\mathbf{E}, \mathbf{F}$ are the convective vectors; $\mathbf{E}_v, \mathbf{F}_v$ are the viscous terms; $\mathbf{H}$ is the chemical source term, and the species mass fraction ω is defined as

$$\frac{\partial}{\partial t}(\rho\omega) + \frac{\partial}{\partial m}(\rho u_m \omega) = \frac{\partial}{\partial m} \left[\left(\frac{\mu}{Pr} + \frac{\mu_t}{\sigma_c} \right) \frac{\partial \omega}{\partial m} \right] \quad (2)$$

$m = x, y$

where, ρ, u_m, Pr , and σ_c are the density, velocity components, Prandtl number and constant coefficient, respectively; $\mu = \mu_l + \mu_t$ is the total viscosity with μ_l and μ_t being the laminar and turbulent viscosities.

The calculations have been carried out using the fully implicit finite volume method, and numerical upwind schemes are adopted to ensure global convergence of mass, momentum, energy, and species. To capture the flow features accurately, the discretization of the convective terms is done by a second-order upwind-difference scheme. The turbulence model applies the two-equation RNG $k-\epsilon$ model with non-equilibrium wall functions^[17].

2.2 Kerosene combustion kinetics mechanism

Derived from petroleum, kerosene fuel is a complex mixture of many components, whose exact composition and properties vary from batch to batch, and it is reported that kerosene consists of 10 hydrocarbons containing 10–16 carbon atoms per molecule^[18]. Obviously, 10 species for kerosene would be highly inefficient in any kind of performance calculations, so surrogate fuel models and reduced chemical kinetics

mechanisms are usually adopted to simulate the kerosene combustion. Several surrogate fuel models, such as $C_{10}H_{19}$, $C_{12}H_{23}$, $C_{12}H_{24}$ and $C_{12}H_{26}$, have been used to represent kerosene so far, whereas the surrogate fuel $C_{12}H_{23}$ ^[18-20] matches reasonably well with the thermophysical-chemical characteristics of aviation kerosene including averaged molecular weight, heat of combustion, etc. In this study, a 10-species and 13-step reduced kerosene combustion kinetics mechanism given in Table 1^[20-21], which applies the Arrhenius's laminar finite rate model, is em-

ployed to predict the chemical non-equilibrium flow in scramjet SERN. The first chemical equation in Table 1 is the decomposition reaction of kerosene surrogate fuel $C_{12}H_{23}$, and the M term in Eq. (2) – Eq. (6) is third-body collision partner, which does not actively participate in reactions. The reaction rate for each elementary step is in Arrhenius form as in Eq. (3), where A is the pre-exponential constant; T is the temperature; β is the temperature dependency exponent; and E is the activation energy.

$$k = AT^\beta e^{-E/RT} \quad (3)$$

Table 1 Reduced kerosene combustion kinetics mechanism (units: cm-s-mol-cal-K)^[20-21]

No.	Chemical equation	A	β	E/cal
1	$2C_{12}H_{23} + 12O_2 \Rightarrow 24CO + 23H_2$	1.80×10^3	0	30 000
2	$M + O + O = O_2 + M$	2.55×10^{18}	-1	0
3	$M + H + H = H_2 + M$	5.00×10^{18}	0	0
4	$M + H + O = OH + M$	1.00×10^{16}	0	0
5	$M + H + OH = H_2O + M$	8.40×10^{21}	-2	0
6	$M + CO + O = CO_2 + M$	6.00×10^{13}	0	0
7	$H_2 + O_2 = OH + OH$	1.70×10^{13}	0	47 803.02
8	$OH + H_2 = H_2O + H$	2.19×10^{13}	0	51 437.4
9	$OH + OH = H_2O + O$	6.02×10^{12}	0	1 092.3
10	$O + H_2 = H + OH$	1.80×10^{10}	1	8 897.28
11	$H + O_2 = O + OH$	1.22×10^{17}	-0.91	16 620.8
12	$CO + OH = H + CO_2$	4.00×10^{12}	1	8 003.58
13	$CO + O_2 = O + CO_2$	3.00×10^{12}	1	49 650

2.3 Discrete-phase model

In this investigation, the strut-based fuel injectors are modeled as surface injectors, wherein droplets are injected from each discretized face of injector with constant diameter. Since kerosene fuel is injected in liquid phase in the form of droplets, the Lagrangian tracking method is adopted for the DPM to characterize the flow behavior of the dispersed-phase fluid. In consideration of each particle of the dispersed phase interacting with the continuous phase and other particles individually, tracking the independent particles through the flowfield is the most widely applied method. Mass, momentum,

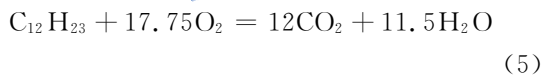
and energy transfer between the two phases are taken into account in the simulation. Besides, the drag force on the dispersed droplets is calculated by using the spherical law^[22], and the dispersive effect of the instantaneous velocity fluctuations of the turbulent continuous phase flowfield on the droplet trajectory is accounted for applying an implicit tracking model. However, droplet collision and breakup have been ignored in the analysis.

2.4 Boundary conditions

In the earlier studies^[4,23], under the condition of typical scramjet operating Mach number $Ma=6$ and altitude $H=25$ km, the freestream

static pressure and static temperature were approximate 2550 Pa and 220 K, respectively. Considering the flow compression and frictional heating inside the intake, ideal air (the mass fraction of O_2 is 0.254, and the rest is N_2) enters the combustor with the inlet conditions of stagnation pressure, stagnation temperature and Mach number specified 1.0 MPa, 2000 K and 1.5, respectively. Liquid kerosene is injected from six injection surfaces in the form of droplets with uniform diameter of $0.1 \mu\text{m}$ at 350 K. The scramjet equivalent mixture ratio ϵ is defined as in Eq. (4) in accordance with the kerosene global reaction Eq. (5) described by the surrogate fuel model $C_{12}H_{23}$ in this work, where $\dot{m}_{\text{kerosene}}$ is the kerosene mass flow, and M is molar mass; ω_{O_2} is the O_2 mass fraction of the ideal air. To investigate the complex non-equilibrium flow features in the SERN and to obtain the thrust characteristics for chemical non-equilibrium effects, various numerical simulations are performed with different kerosene injection positions and equivalent mixture ratios. In addition, all the flow variables at outlet are determined from the interior of the computational domain by extrapolation, and the walls are considered stationary and adiabatic.

$$\epsilon = 17.75 \frac{\dot{m}_{\text{kerosene}} M_{O_2}}{m_{\text{air}} \omega_{O_2} M_{\text{kerosene}}} \quad (4)$$



3 Results and discussion

3.1 Combustion feature and SERN entry conditions

To depict the combustion development process, the total temperature distribution inside the strut-based combustor at equivalent mixture ratio $\epsilon=0.5$ is presented in Fig. 4. Because of hypothermal liquid kerosene fuel injection, the total temperature is seen to reduce downstream of the injector struts and again rise further downstream due to kerosene combustion. As a close-up view in Fig. 3, the localized backflow and vortices at the low velocity regions behind the flame-hold struts contribute to the mixing of

the kerosene with the oxidizer. The total temperature downstream of the flame-hold struts varies with the heat release associated with the mixing effect and relevant reaction processes. Axial distributions of the area-averaged static temperature T_{mean} , Ma_{mean} , total pressure $p_{t,\text{mean}}$ and mass-averaged species mass fractions at various cross sections in the combustor are illustrated in Fig. 5. Since trifling flow expansion upstream of the struts, the area-averaged static temperature decreases slowly and the Mach number rises gently. Because of oblique shock from the struts and intense heat release, the area-averaged Mach number reduces significantly within the struts region and again accelerates downstream of the struts due to divergence of the combustor, but the area-averaged static temperature continuously ascends from the first stage of strut group. In addition, the loss of area-averaged total pressure owing to the interaction of shock and combustion in the strut-based combustor is about 0.35 MPa in this case. The mass-averaged species mass fractions in Fig. 5 are 0 until the kerosene injection and dissociation, and then the mass fractions of the intermediate particle OH, the final products CO_2 and H_2O are unceasingly going up in the combustor.

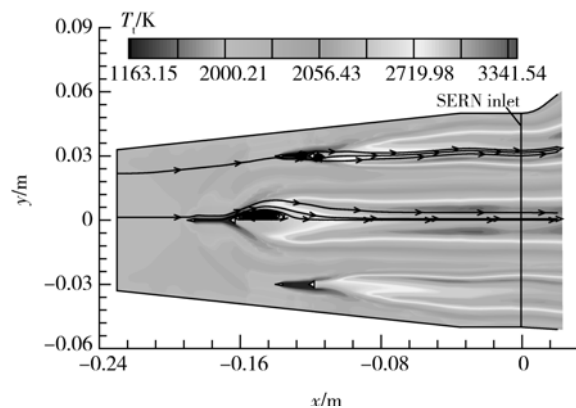


Fig. 4 Total temperature distribution in strut-based combustor at $\epsilon=0.5$

Distribution curves of the primary SERN inlet parameters at equivalent mixture ratio $\epsilon=0.5$ with equal mass flow rate for all six injection surfaces are given in Fig. 6. Every parameter is

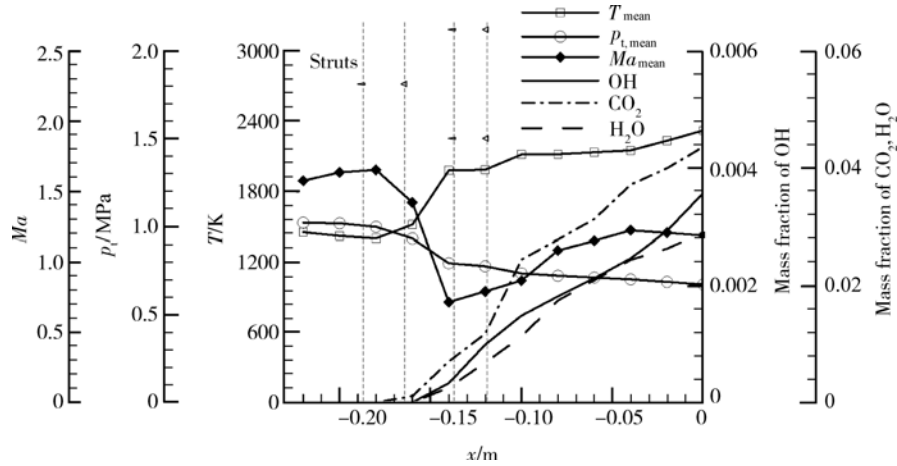


Fig. 5 Variation of average parameters along strut-based combustor axis at $\epsilon=0.5$

seen to fluctuate along the inlet cross section corresponding with the strut position, nevertheless small discrepancy occurs between the central and side regions due to the different distances from the SERN entrance of the struts. This indicates that various SERN entry conditions could be conveniently modeled by changing the injector strut position and controlling the mass flow rate of every injector. In addition, it is to be noted that the incomplete combustion in the strut-based combustor brings considerable mass fraction of intermediate product CO at the nozzle inlet, and then the recombination reactions of CO and other intermediate particles will be carried on in the single expansion ramp nozzle. Fig. 7 shows the primary area-averaged SERN inlet parameters for different equivalent mixture ratios. The combustion efficiency η in this figure is defined as the ratio of the actual CO_2 formed at the SERN entrance to the ideal CO_2 that can be formed from the reaction Eq. (5). It reveals that higher equivalent mixture ratio leads to higher area-averaged pressure p_{mean} and temperature T_{mean} but lower area-averaged Mach number Ma_{mean} , combustion efficiency η_{mean} , total pressure recovery coefficient σ_{mean} and specific heat ratio γ_{mean} of the SERN inlet cross section because of higher heat release and stronger shock waves in the strut-based combustor. The variation ranges of these mean parameters (with p_{mean} being 0.19 MPa to 0.37 MPa, T_{mean} being

1680 K to 2420 K, Ma_{mean} being 1.17 to 1.57, η_{mean} being 0.51 to 0.85, σ_{mean} being 0.67 to 0.75, and γ_{mean} being 1.28 to 1.30, respectively) are similar with the preceding investigations by WANG et al., Manna et al., Ramya et al., Pierce et al., LIU et al. [4,7,14,24-25], which demonstrates that the computed SERN entry conditions by the strut-based combustor are appropriate and reliable in this work.

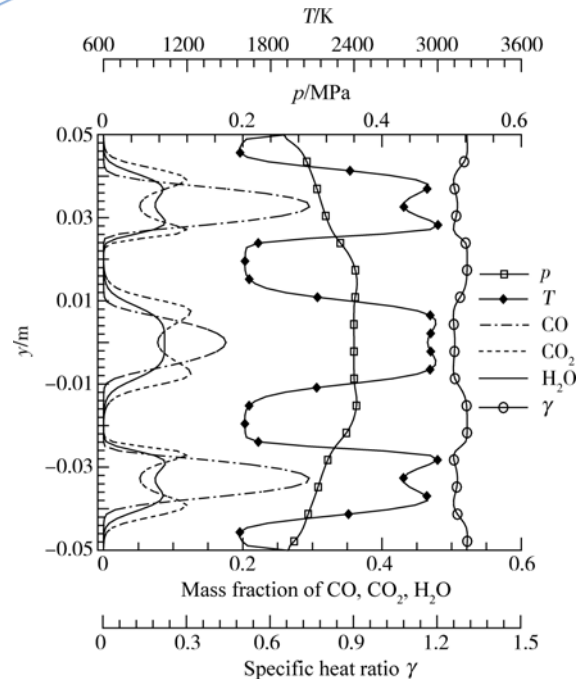


Fig. 6 Distribution curves of primary SERN inlet parameters at $\epsilon=0.5$

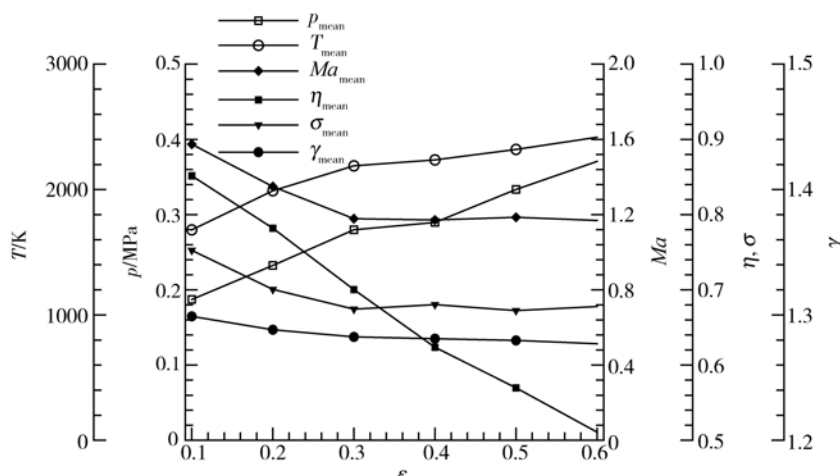


Fig. 7 Area-averaged SERN inlet parameters for different equivalent mixture ratios

3.2 Chemical non-equilibrium effects

Distribution of mass fraction of OH in the SERN and variations of mass-averaged species mass fractions along the SERN length which have taken the free stream off at equivalent mixture ratio $\epsilon = 0.5$ are presented in Fig. 8 and Fig. 9, respectively. Because the predominant recombination reactions are ongoing throughout the SERN, the mass fractions of intermediate products O, H, OH and CO continuously decrease, whereas the final product CO_2 forms unremittingly, which demonstrates that the flow inside the SERN behaves in chemical non-equilibrium character. Furthermore, the noteworthy variation rates of all these species are seen up

to $x = 600$ mm, and beyond that, almost all of the species mass fractions are seemingly invariable (with inappreciable variation ranges) due to the approximate frozen flow incurred by the low temperature in the region where $x > 600$ mm.

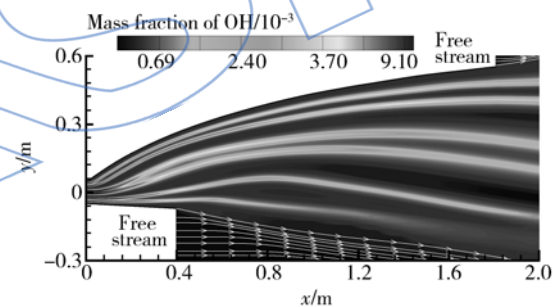


Fig. 8 Contours of OH mass fraction in SERN at $\epsilon = 0.5$

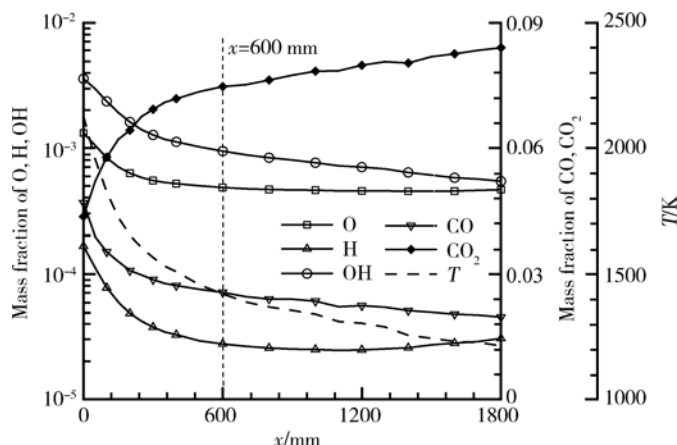


Fig. 9 Variations of mass-averaged species mass fractions along SERN length at $\epsilon = 0.5$

To investigate the chemical non-equilibrium effects in the SERN flowfield, the variations of mass-averaged flow parameters with the free stream eliminated along the SERN length and the distributions of SERN wall pressures of the reacting flow and frozen flow (with the selfsame nozzle inlet conditions) at equivalent mixture ratio $\epsilon=0.5$ are compared in Fig. 10 and Fig. 11, respectively. The mass-averaged pressure, temperature, total temperature and the distributional wall pressures of the non-equilibrium flow are

seen to be obviously higher than those of the frozen flow, but the mass-averaged Ma behaves contrarily owing to the interaction of flow expansion and significant amount of heat release revealed from the total temperature variation curve in the non-equilibrium flowfield. Moreover, the added wall pressure of the non-equilibrium flow relative to the frozen flow leads to about 10.8% and 23.6% increment of the SERN thrust and lift at $\epsilon=0.5$, respectively.

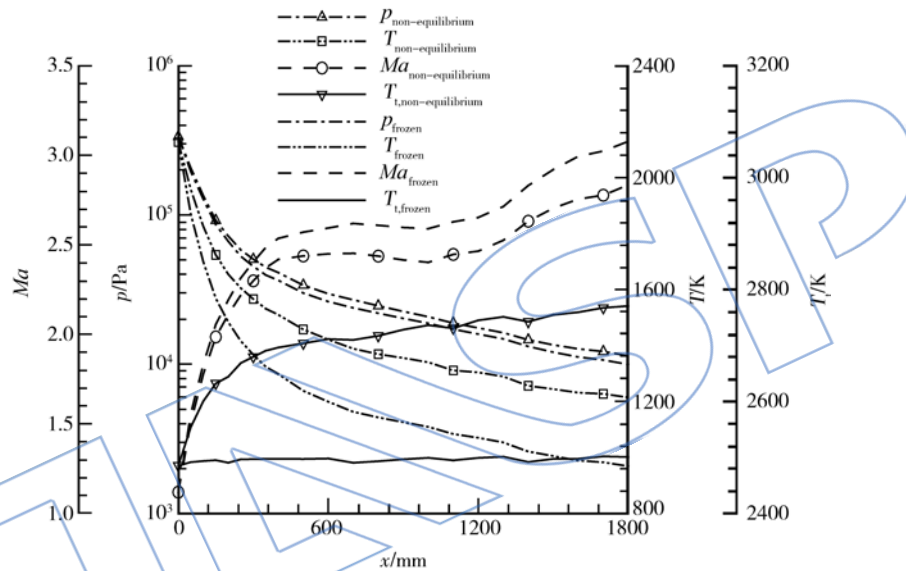


Fig. 10 Comparison of variations of mass-averaged non-equilibrium and frozen flow parameters along SERN length at $\epsilon=0.5$

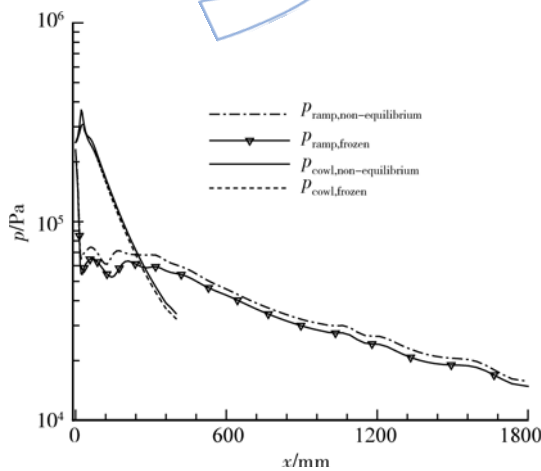


Fig. 11 Comparison of SERN wall pressure distributions of non-equilibrium and frozen flow at $\epsilon=0.5$

3.3 Influence of fuel injection position

Four different injection cases at equivalent

mixture ratio $\epsilon=0.1$ given in Table 2 are used to investigate the influence of fuel injection positions on the chemical non-equilibrium flow in SERN. The variations of mass-averaged total temperature T_t and species mass fractions along SERN length which have eliminated the free stream are compared in Fig. 12 for these cases. For case 4, attributing to the distributed fuel in-

Table 2 Cases for different fuel injection positions

Case	Injector strut		
	Upper	Middle	Nether
1	×	✓	×
2	✓	✓	×
3	×	✓	✓
4	✓	✓	✓

jection pattern, the total temperature and final product CO_2 in SERN are the highest, and the intermediate product OH is the lowest among these cases, whereas all of the parameters behave quite the contrary for case 1. On the other hand, it is to be noted that the variation ranges of the aforementioned parameters in SERN for case 4 are the smallest, but the largest for case

1. In addition, the values and variation ranges of all the parameters for case 2 and case 3 are between those for case 1 and case 4. This indicates that the more distributed fuel injection pattern leads to higher combustion efficiency in combustor but lower chemical non-equilibrium effects in SERN.

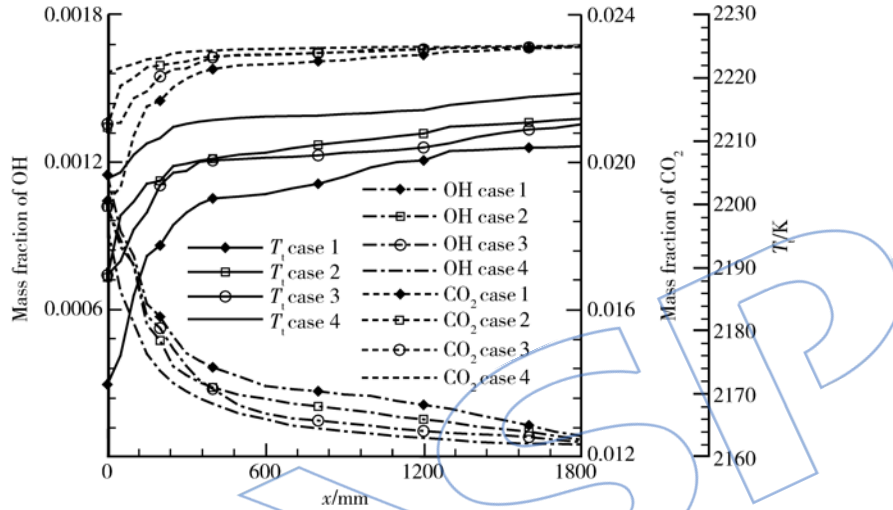


Fig. 12 Variations of mass-averaged parameters along SERN length for different fuel injection position cases

The thrust coefficient C_F and lift coefficient C_L are adopted to evaluate the SERN performance in this paper, which are defined as in Eq. (6) and Eq. (7), where F , L , q and A are the nozzle thrust, nozzle lift, dynamic pressure in flight and capture area of the scramjet intake port, respectively. The SERN C_F and C_L of the four different fuel injection position cases are compared in Fig. 13, where the nozzle thrust F and nozzle lift L are calculated from the pressure integral on the ramp and cowl. In addition, the dynamic pressure p is 64 238 Pa (with operating Mach number and altitude are 6 and 25 km, respectively), and the capture area A is 0.5 m^2 . In this figure, the variable δ defined as the SERN performance increment of chemical non-equilibrium flow relative to frozen flow is described in Eq. (8). Also due to the distributed fuel injection pattern and intense heat released in combustor, the SERN C_F and C_L for case 4 are highest among these cases, but the lowest for case 1.

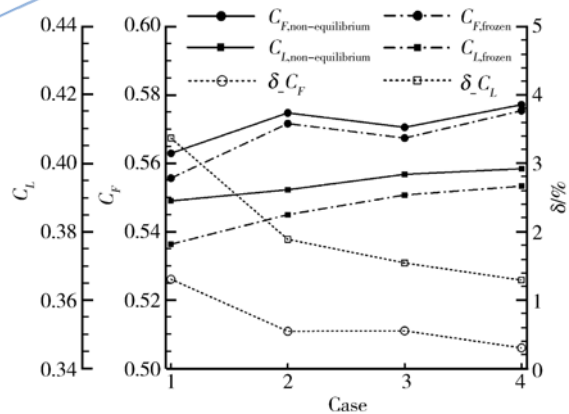


Fig. 13 Comparison of SERN performance for different fuel injection position cases at $\epsilon=0.1$

Moreover, the thrust coefficient C_F for case 2 is slightly higher than that for case 3, whereas the lift coefficient C_L for case 2 is negligibly lower than that for case 3. As a consequence, it implies that the combustion domain abutting ramp would conveniently transform the releasing heat into SERN thrust, whereas the combustion domain adjacent cowl would result in comparatively

higher SERN lift. Besides, the SERN thrust coefficient C_F and lift coefficient C_L of non-equilibrium flow are seen to be significantly higher than those of frozen flow. The maximum and minimum performance increments (δ_{CF} and δ_{CL}) owing to the chemical non-equilibrium effects occur at case 1 and case 4, respectively. Furthermore, the SERN lift coefficient increment δ_{CL} is seen to be more prominent than the thrust coefficient increment δ_{CF} for all the four cases.

$$C_F = F/(q \cdot A) \quad (6)$$

$$C_L = L/(q \cdot A) \quad (7)$$

$$\delta = \frac{C_{F(L), \text{non-equilibrium}} - C_{F(L), \text{frozen}}}{C_{F(L), \text{frozen}}} \times 100\% \quad (8)$$

3.4 Influence of equivalent mixture ratio

Getting rid of the free stream, variations of mass-averaged CO_2 mass fraction and total temperature T_t along the SERN length for different equivalent mixture ratio cases with equal fuel injection rate for all injector struts are compared in Fig. 14 and Fig. 15, respectively. It can be seen that the value and variation range of the final product CO_2 in SERN increase continuously with rise in equivalent mixture ratio ϵ , and yet the increase rates are slower at the higher ϵ . Besides, the increased variation range of mass fraction of CO_2 can be explained to result by the stronger chemical non-equilibrium effects in SERN. These are consistent with the total temperature variation trend. The SERN thrust coefficient C_F and lift coefficient C_L of the non-equilibrium flow and frozen flow are compared in Fig. 16. The calculation results show that the SERN performance of chemical non-equilibrium flow obviously preponderates over that of the frozen flow. While the equivalent mixture ratio ϵ increases, the SERN C_F and C_L rise gradually, and thrust coefficient increment and lift coefficient increment (δ_{CF} and δ_{CL}) become higher as well. In addition, due to the chemical non-equilibrium effects in SERN, the lift coefficient increment δ_{CL} is more dominant relative to the thrust coefficient increment δ_{CF} . To be specific, the minimum δ_{CF} and δ_{CL} occurring at $\epsilon = 0.1$ are 0.3% and 1.3%, respectively; and the maximum δ_{CF}

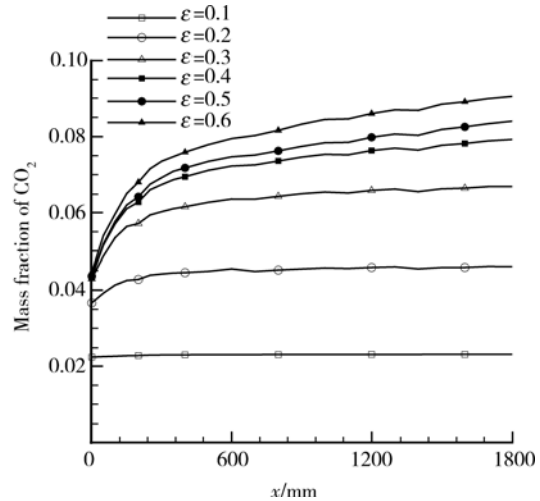


Fig. 14 Variation of mass-averaged CO_2 mass fraction along SERN length for different equivalent mixture ratio cases

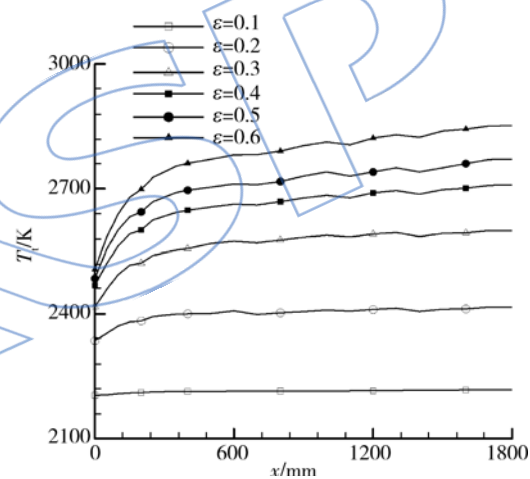


Fig. 15 Variation of mass-averaged total temperature along SERN length for different equivalent mixture ratio cases

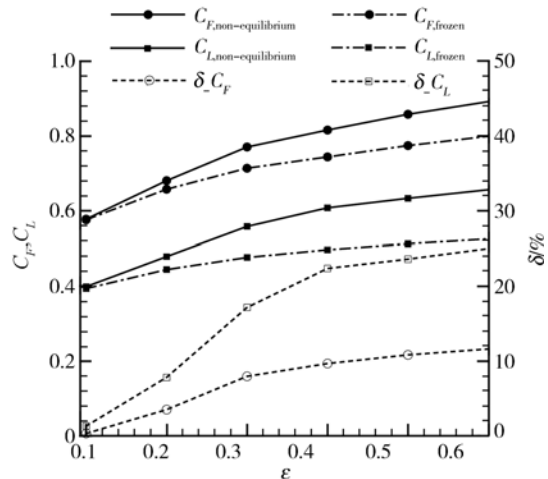


Fig. 16 SERN performance vs. equivalent mixture ratio

and δ_{CL} occurring at $\epsilon=0.6$ are 11.6% and 25%, respectively.

4 Conclusions

Numerical simulations are carried out to analyze the chemical non-equilibrium flow and performance of scramjet SERN with a strut-based liquid-kerosene-fueled combustor. Two-dimensional RANS equations are solved with the species conservation equation for continuous phase and the RNG $k-\epsilon$ turbulence model. The flow behavior of liquid-kerosene droplets is characterized by employing the discrete-phase model with Lagrangian tracking method. Combustion is modeled by kerosene surrogate fuel $C_{12}H_{23}$'s 10-species and 13-step reduced reaction kinetics mechanism applying the Arrhenius's laminar finite rate model. The calculation results show that the strut-based combustor could conveniently simulate various SERN entry conditions, which is similar to many preceding investigations, by changing the injector strut position and controlling the mass flow rate of every injector. The computed mass-averaged properties along SERN length demonstrate that chemical non-equilibrium effects behave in the whole SERN, especially noteworthy in the initial flow expansion region, which leads to obviously higher SERN performance of the non-equilibrium flow than that of frozen flow. The comparisons of different fuel injection position cases revealed that the more distributed fuel injection pattern plays a significant role in resulting in higher combustion efficiency in combustor but lower chemical non-equilibrium effects in the SERN. Through comparison of nozzle thrust coefficient and lift coefficient for different equivalent mixture ratio cases, it reasons out that while the equivalent mixture ratio ϵ increases, the SERN thrust coefficient C_F and lift coefficient C_L rise gradually, and the increment of non-equilibrium flow relative to frozen flow (δ_{CF} and δ_{CL}) become higher as well. To be specific, the maximum δ_{CF} and δ_{CL} in this work occurring at $\epsilon=0.6$ are 11.6% and 25%, respectively.

References:

- [1] Kumaran K, Babu V. Mixing and combustion characteristics of kerosene in a model supersonic combustor[J]. Journal of Propulsion and Power, 2009, 25(3): 583-592.
- [2] YU Yong, DING Meng, LIU Weidong, et al. Experimental study of supersonic combustion of kerosene[J]. Journal of National University of Defense Technology, 2004, 26(1): 1-4. (in Chinese)
- [3] Yu G, Li J G, Chang X Y, et al. Investigation of kerosene combustion characteristics with pilot hydrogen in model supersonic combustor[J]. Journal of Propulsion and Power, 2001, 17(6): 1263-1272.
- [4] WANG Xinyue, YANG Zhenpeng, WANG Yanqing. Effects of non-equilibrium chemical reaction flow on the performance of scramjet nozzle[J]. Journal of Aerospace Power, 2009, 24(5): 1022-1027. (in Chinese)
- [5] Thomas L, Wolfgang W K. Computation of a nonequilibrium expansion flow in a single expansion ramp nozzle[J]. Journal of Propulsion and Power, 2001, 17(6): 1353-1360.
- [6] Kaneko M, Menshov I, Nakamura Y. Numerical simulation of non-equilibrium flow in high-enthalpy shock tunnel with EIH scheme[R]. AIAA-2001-2860, 2001.
- [7] Manna P, Behera R, Chakraborty D. Liquid-fueled strut-based scramjet combustor design: a computational fluid dynamics approach[J]. Journal of Propulsion and Power, 2008, 24(2): 274-281.
- [8] Malo-Molina F J, Gaitonde D V, Ebrahimi H B. Numerical investigation of a 3D chemically reacting scramjet engine at high altitudes using JP8-air mixtures [R]. AIAA-2005-1435, 2005.
- [9] Rajasekaran A, Babu V. Evaluation of a ramp cavity based concept supersonic combustor using CFD[J]. Progress in Computational Fluid Dynamics, 2009, 9(1): 16-19.
- [10] Baurle R A, Eklund D R. Analysis of dual-mode hydrocarbon scramjet operation at Mach 4—6.5[J]. Journal of Propulsion and Power, 2002, 18(5): 990-1002.
- [11] Christopher R, Joseph A S. Experimental and numerical studies of a strut injector for round scramjet combustors [R]. AIAA-2009-7313, 2009.
- [12] Marius C B, Tobias S, Jaechul C, et al. Numerical study of supersonic combustion processes with central strut injection[J]. Journal of Propulsion and Power, 2010, 26(4): 869-874.
- [13] Kumaran K, Behera P R, Bahu V. Numerical investigation of the supersonic combustion of kerosene in a strut-based combustor[J]. Journal of Propulsion and Power, 2010, 26(5): 1084-1091.
- [14] Ramya P H, Marathe A G. A computational study on supersonic combustion with struts as flame holder [R]. AIAA-2008-4712, 2008.
- [15] Rajasekaran A, Satishkumar G, Babu V. Numerical simulation of the supersonic combustion of kerosene in a model

- combustor[J]. Progress in Computational Fluid Dynamics, 2009, 9(1): 30-42.
- [16] ZHOU Zheng, NI Hongli, HE Xuzhao, et al. Optimization design of single expansion ramp nozzle based on Rao's method[J]. Journal of Propulsion Technology, 2009, 30(4): 451-456. (in Chinese)
- [17] LIU Ouzi, CAI Yuanhu, HU Yuli, et al. The turbulence models for numerical analysis of liquid kerosene supersonic combustion[J]. Acta Aerodynamica Sinica, 2007, 25(3): 362-367. (in Chinese)
- [18] Amsden A A. KIVA-III: a KIVA program with block structure mesh for complex geometry [R]. LA-12503-MS, 1993.
- [19] HUANG Shenghong, XU Shengli, LIU Xiaoyong. Combustion flow of kerosene-fueled scramjet with 3D cavity: III [J]. Journal of Propulsion Technology, 2005, 26(2): 101-105. (in Chinese)
- [20] Ten-See W. Thermophysics characterization of kerosene combustion [J]. Journal of Thermophysics and Heat Transfer, 2001, 15(2): 140-147.
- [21] Kundu K P, Penko P F, Yang S L. Simplified jet-A/air combustion mechanisms for calculation of NOx emissions [R]. AIAA 98-3986, 1998.
- [22] Arbor A. FLUENT 6.3 User's Guide[M]. [S. l.]: Ansys Incorporation, 2006.
- [23] WU Xianyu. Research on design and optimization of integrated scramjet flowpath[D]. Changsha: National University of Defense Technology, 2007. (in Chinese)
- [24] Pierce M, Ely W. A computational exploration of the importance of three-dimensionality, boundary layer development, and flow chemistry to the prediction of scramjet nozzle forces and moments[R]. AIAA 91-5059, 1991.
- [25] LIU Ouzi, CAI Yuanhu, HU Yuli, et al. Experimental investigation of kerosene fuel combustion in the supersonic flow[J]. Journal of Propulsion Technology, 2005, 26(3): 276-279. (in Chinese)